Pergamon

PII: S0042-6989(97)00230-7

Vision Res., Vol. 38, No. 4, pp. 499–512, 1998

Printed in Great Britain
0042-6989/98 $19.00 + 0.00

Accuracy of Estimating Time to Collision using Binocular and Monocular Information*

R. GRAY,† D. REGAN‡§

Received 20 March 1997; in revised form 4 June 1997

We measured both the just-noticeable difference in time to collision (TTC) with an approaching object, and the absolute accuracy in estimating TTC in the following cases: only binocular information available; only monocular information available; both binocular and monocular information available as in the everyday situation. Observers could *discriminate* trial-to-trial variations in TTC on the basis of binocular information alone: the just-noticeable difference in TTC (5.1–9.8%) was the same for a small (0.03 deg) target and for a large (0.7 deg) target. In line with previous reports, when only monocular information was available, the just-noticeable difference in TTC was 5.8–12% for the large target. However, observers could not reliably discriminate trial-to-trial variations in TTC with the small target when only monocular information was available. When both binocular and monocular information was available, the just-noticeable difference in TTC for the large target was not significantly different from when only binocular or only monocular information was available. Observers could make reliable estimates of *absolute* TTC using binocular information only. Errors ranged from 2.5 to 10% for the large target, and 2.6 to 3.0% for the small target, all being overestimates. Errors for the small target were the same or lower than errors for the large target. Observers could make reliable estimates of TTC with the large target using monocular information only. Errors ranged from 2.0 to 12%, all being underestimates. Since monocular information did not provide a basis for reliable estimates of absolute TTC with the small target we conclude that, in everyday conditions, accurate estimates of TTC with small targets are based on binocular information when the object is small and is no more than a few metres away. Errors in estimating absolute TTC were lower in the case where both binocular and monocular information were available (as in the everyday situation) than when only binocular information or only monocular information was available. Errors ranged from 1.3 to 2.7%. An error of 1.3% approaches the accuracy required to explain the ±2.0–2.5 msec accuracy with which top sports players can estimate the instant of impact between bat and ball.

Time to collision   Looming   Stereomotion   Collision avoidance   Motion perception

INTRODUCTION

The ability to judge time to collision sufficiently ahead of time to allow an appropriate motor response is important in a wide variety of situations ranging from hitting or catching a ball to the more threatening situations encountered in highway driving and aviation. Wheatstone (1852) showed that isotropic expansion of an object's retinal image produces the compelling impression that the object is moving on a collision course towards the observer's eye, even when the object is stationary. Hoyle (1957) showed theoretically that the monocular retinal image of an approaching rigid sphere of angular subtense θ moving at constant speed in a straight line directly towards an observing eye contains a correlate of the time to collision (T) with the approaching sphere. In particular:

$$T \approx \frac{\theta}{\mathrm{d}\theta/\mathrm{d}t}, \qquad (1)$$

provided that θ is small (Hoyle, 1957). (The error is approximately 1.0% for $\theta = 10$ deg, 1.5% for $\theta = 20$ deg and 5.4% for $\theta = 30$ deg).

Following Lee (1976), several authors have suggested that humans take advantage of equation (1) in highway driving, in sporting activities and in aviation (Lee & Lishman, 1977; Lee, Lishman, & Thomson, 1982; Lee,

*Part of the material reported in this paper was presented at the annual meeting of the Association for Research in Vision and Ophthalmology [Gray, R. and Regan, D. (1996). Estimates of time to collision based on binocular and monocular visual information. *Investigative Ophthalmology and Visual Science, 37*, S652].

†Department of Psychology, York University, 4700 Keele Street, North York, Ontario, Canada M3J 1P3.

‡Department of Biology, York University, 4700 Keele Street, North York, Ontario, Canada M3J 1P3.

§To whom all correspondence should be addressed [*Tel*: (416) 736 5627; *Fax*: (416) 736 5814; *Email*: martin@george.psych.yorku.-ca].

Young, Reddish, Lough, & Clayton, 1983; Todd, 1981; Warren, Young, & Lee, 1986; DeLucia, 1991; Savelsbergh, Whiting, & Bootsma, 1991; Schiff & Detwiler, 1979; Bootsma & van Wieringen, 1990; Cavallo & Laurent, 1988; Regan, 1991a, 1995; Kruk & Regan, 1983; Karnavas, Bahill, & Regan, 1990).

Formal laboratory studies have shown that when the stimulus falls within the central visual field, observers can have discrimination thresholds for the ratio $\theta/(d\theta/dt)$ as low as 7–13%, while totally ignoring variations in θ and $d\theta/dt$ (Regan & Hamstra, 1993; Regan & Vincent, 1995). However, a low discrimination threshold, though requisite for high accuracy, does not necessarily imply high accuracy: observers might consistently overestimate or underestimate absolute time to collision.

In the world outside the laboratory, the accuracy with which top sports players can judge the time of arrival of an approaching ball is remarkable: an accuracy of ±2.0–2.5 msec has been claimed for national-level cricket and table-tennis players, and on the face of it this would call for a discrimination threshold considerably lower than 7–13% (Regan, Beverley & Cynader, 1979; Bootsma & van Wieringen, 1990).

When the approaching object is too small, the correlate of time to collision expressed in equation (1) is not available to the observing eye, because the rate of expansion of the object's retinal image is undetectable, even when the object is close (see Appendix I). This does not imply, however, that time to collision cannot, in principle, be estimated. Wheatstone (1852) showed that when an object's retinal images in the left and right eyes are caused to move away from each other horizontally at equal speeds, observers report a compelling impression that the object is approaching on a collision course, even though the object is actually stationary. If an observer perceives an object's speed of motion-in-depth to be high, it seems plausible that the observer would estimate the time to collision with that object to be shorter than the time to collision with a second object at the same perceived distance, whose perceived speed of motion-in-depth is low. (Of course, this tells us nothing about the absolute accuracy of such estimates.) Further to this point, it is known that the sensation of motion-in-depth created by retinal image expansion is qualitatively identical to the sensation of motion-in-depth created by rate of change of disparity. For example, the motion-in-depth aftereffect caused by adapting to a contracting target can be cancelled by stimulating either with a rate of expansion or with a rate of change of disparity (Regan & Beverley, 1979).

It has been shown theoretically that a binocular correlate of time to collision (T) is available for small as well as for large objects. In particular:

$$T \approx \frac{I}{D(d\delta/dt)}, \qquad (2)$$

where D is the object's distance, I is the interpupillary separation and $(d\delta/dt)$ is the rate of change of relative disparity (see Appendix I). However, although a substantial number of studies on stereomotion have been published (reviewed in Tyler, 1991; Regan, 1991b; and Collewijn & Erkelens, 1990), as have a substantial number of studies on time to collision (reviewed in Tresilian, 1995), there have been very few reports of data on the use of binocular information in estimating time to collision. This might seem a curious omission given that the monocularly available ratio $\theta/(d\theta/dt)$ is an ineffective indicator of time to collision for small objects (Regan & Beverley, 1979). Among the possible reasons for this omission are the following. (a) Viewing distance enters into equation (2), and the weight of evidence is that we are poor at judging the absolute distance of objects further than a few metres away from the head (Collewijn & Erkelens, 1990). (b) The sensation of motion-in-depth generated by a given rate of change of disparity is quite different in different visual spatial environments. In particular, the sensation of motion-in-depth is enhanced by the presence of stationary reference marks close to the moving object's retinal images (Tyler, 1975; Erkelens & Collewijn, 1985a,b; Regan, Erkelens, & Collewijn, 1986a). (c) Many subjects have areas of the visual field that are selectively blind to stereomotion (Richards & Regan, 1973; Regan, Erkelens, & Collewijn, 1986b; Hong & Regan, 1989).

The theoretical and physiological factors that determine the relative importance of monocular and binocular correlates of motion-in-depth have been discussed in some detail (Regan & Beverley, 1978a, 1979). For our present purpose we note that, as indicated by equation (3), the ratio between the monocular $(d\theta/dt)$ and binocular $(d\delta/dt)$ correlates of an approaching object's motion-in-depth *is not affected by the object's distance* (D), but is inversely proportional to 2s, the object's absolute (as distinct from angular) width (Regan & Beverley, 1979, see Appendix I).

$$\frac{d\theta/dt}{d\delta/dt} \approx \frac{2s}{I}. \qquad (3)$$

For example, if a person whose eyes are 6 cm apart views an approaching sphere, the ratio between the magnitudes of the monocular and binocular cues to depth is 1:6 for an approaching sphere of diameter 1 cm, 1:12 for an approaching sphere of diameter 0.5 cm, and so on.

Below, we compare judgements of time to collision using the $I/[D(d\delta/dt)]$ cue alone, with judgements using the $\theta/(d\theta/dt)$ cue alone and also with judgements when both cues are available. In the main experiments we chose a range of values of viewing distance, time to collision and absolute size of the simulated sphere that placed both monocular and binocular correlates of motion-in-depth well above psychophysical detection thresholds and of approximately similar importance. For completeness, however, we also investigated a situation where the monocular correlate of time to collision was much weaker than the binocular correlate.

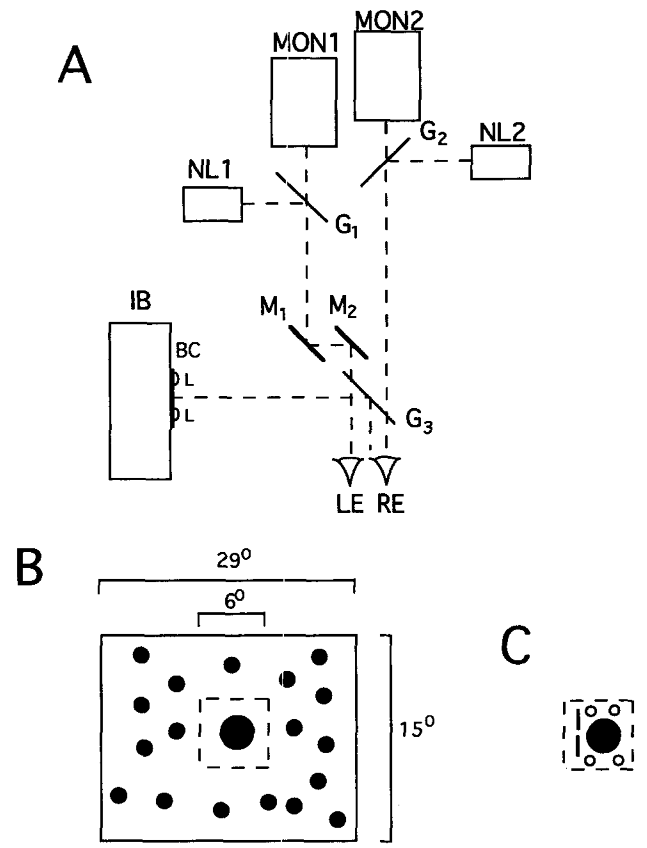

FIGURE 1. (A) depicts the optical arrangement. MON 1 and MON 2: monitors. NL1 and NL2: nonius line displays. G_1, G_2 and G_3: thin glass sheets. M1 and M2: mirrors. LE: left eye. RE: Right eye. IB: illuminated background. BC: black card. L: light emitting diode (LED). (B) shows what the observer saw. The dashed line indicates the position of the black card. The grey disc represents the binocularly fused bright spot. (C) shows the centre of (B) in more detail, including the nonius lines and four LEDs.

GENERAL METHODS

Apparatus

A uniformly illuminated circular spot of mean luminance 21 cd/m^2 was displayed on each of two electrostatically driven monitors (Tektronix model 608 with green P31 phosphor). The location and size of the spot was varied by analogue electronics of our design. Each monitor ran at 50 frames/sec.

Except when stated otherwise, the two monitors (MON1 and MON2) were viewed dichoptically from a distance of 168 cm via the optical arrangement shown in Fig. 1(A). Front-surface mirrors M1 and M2 were arranged so that the left eye viewed only MON1 and the right eye viewed only MON2. Thin sheets of glass (G1 and G2) were placed so that nonius lines could be optically superimposed on monitors MON1 and MON2, respectively. The nonius lines, displayed on Tektronix 604 monitors, were each 0.44 deg high and 0.03 deg wide. Their purpose was to check the accuracy and constancy of the observer's ocular convergence. The upper line (N1) was seen by the left eye and the lower line (N2) was seen by the right eye. When the lines appeared to be collinear, the observer's eyes were accurately converged on the plane of the monitors. A thin sheet of glass (G3) was placed in front of both eyes so as to superimpose an illuminated background (IB) onto the plane of the monitors. The background was green and subtended 29 deg (horizontal) $\times$ 15 deg and had a luminance of 14 cd/m^2. As an aid to convergence, a total of 200 large (0.34 deg diameter) black dots were randomly located over the background. A central 6 $\times$ 6 deg square region of the background was covered by a black card (BC). Stationary reference marks close to the binocularly fused stimulus spot were provided by placing four green LEDs behind small holes (0.15 deg angular subtense) in the black card. Figure 1(B) and (C) gives an impression of what the observers saw. Figure 1(B) shows some of the 200 large black dots with the uniformly illuminated spot (hatched area) at the centre superimposed on the black card (dashed line). Figure 1(C) shows in more detail the black card with the illuminated spot at the centre, the nonius lines and the four LEDs. The observer's head was supported by a chin rest.

Simulation of an object moving in depth

Rather than using a real moving object in our experiments we simulated a moving object by creating the retinal images that would have been produced by a rigid spherical object moving at constant speed along a straight line towards the eye. If the angular subtense and time to collision of a rigid sphere that is moving at constant speed along a straight line passing directly through the eye are, respectively, θ_0 and T at time $t = 0$, then the retinal image size (θt) at time t is given by:

$$\theta_t \approx \frac{\theta_0}{(1 - t/T)} \tag{4}$$

provided that θ_t and θ_0 are small (Regan & Hamstra, 1993). In Experiments 1, 3, 4 and 5 we caused the angular subtense of the spots on both monitors to vary accordingly to equation (4) so as to simulate an approaching sphere. Except when stated otherwise, when we presented monocular information alone, binocular disparity was constant and both eyes saw identical targets.

If the disparity (relative to some fixed point), distance, and time to collision of a point that is moving at constant speed along a straight line that passes between the eyes are, respectively δ_0, D_0 and T at time $t = 0$, then the relative disparity (δ_t) at time $t = 0$ is given by:

$$\delta_t \approx \delta_0 + \frac{It}{D_0 T(1 - t/T)} \tag{5}$$

where I is the observer's interpupillary separation (see Appendix I). In Experiments 1, 2, 4 and 5 we caused the relative disparity of the spots on the two monitors to vary according to equation (5) so as to simulate an approaching sphere. The distance in depth over which the simulated sphere could move without the observer's losing binocular fusion was limited because we instructed the observer not to track the simulated sphere and used nonius lines to check that this instruction was followed. (Observers were instructed to check that the nonius lines were collinear before, during and after the presentation and to abort the trial if there was a breakdown of collinearity. Our observers did not experience difficulty in maintaining collinearity.) To allow the maximum excursion of disparity consistent with binocular fusion, starting disparity was always 0.54 deg uncrossed or divergent (i.e., beyond the fixation point). When we presented only binocular information about time to collision, the sizes of the targets seen by the left and right eyes were constant and identical.

Observers

Five observers were used. Observers 1 (author RG), 2 and 5 were male. Observers 3 and 4 were female. Author DR (a male aged 60 years) carried out preliminary measurements. All subjects had monocular visual acuity of 6/6 or better in both eyes. Observers 2, 3, 4 and 5 were naïve as to the aims of the experiment and were paid at an hourly rate.

EXPERIMENT 1

Methods

Purpose and rationale. The purpose of Experiment 1 was to determine the effect of object size on the relative importance of monocular and binocular information in estimating time to collision.

Outside the laboratory, one is typically required to make an accurate estimate of time to collision with no practice trials, and the stimulus situation never repeats exactly. In such situations a low discrimination threshold for time to collision is requisite for a low absolute error on every single judgement. In Experiment 1 we compared discrimination thresholds for $\theta/(\mathrm{d}\theta/\mathrm{d}t)$ and for $I/D(\mathrm{d}\delta/\mathrm{d}t)$ for two different target sizes.

Apparatus. We used two values of mean target diameter at time $t = 0$: 0.03 deg and 0.7 deg. For the 0.03 deg target, measurements involving the $\theta/(\mathrm{d}\theta/\mathrm{d}t)$ cue were carried out using a single, binocularly viewed monitor at a distance of 21.5 m so as to avoid the use of expanding targets whose linear dimensions were impractically small. At this distance, a disc of diameter 1.2 cm subtended 0.03 deg. Observers wore trial frames holding prisms and lenses that converted the effective viewing distance to approximately 1.68 m, while leaving the angular subtense and rate of change of subtense of the target unaffected. For all other measurements the apparatus was as described in General Methods.

When the ratio $\theta/(\mathrm{d}\theta/\mathrm{d}t)$ was the task-relevant variable, the 64 stimuli consisted of different combinations of $\theta/(\mathrm{d}\theta/\mathrm{d}t)$, $\mathrm{d}\theta/\mathrm{d}t$, θ and $\Delta\theta$, where $\Delta\theta$ was the change in size during the presentation (see Regan & Hamstra, 1993). The mean value of $\theta/(\mathrm{d}\theta/\mathrm{d}t)$ was 2.3 sec, and the presentation duration (Δt) was 700 msec. We arranged that the values of $\theta/(\mathrm{d}\theta/\mathrm{d}t)$, and $\mathrm{d}\theta/\mathrm{d}t$ varied orthogonally within the set of 64 stimuli (i.e., they had zero correlation). To achieve dissociation between $\mathrm{d}\theta/\mathrm{d}t$ and $\theta/(\mathrm{d}\theta/\mathrm{d}t)$, the starting size was varied about the mean by 40%. We chose to dissociate $\theta/(\mathrm{d}\theta/\mathrm{d}t)$ and $\mathrm{d}\theta/\mathrm{d}t$ because it is known that in some situations (e.g., in peripheral vision) large objects appear to approach faster than small objects, even when they have the same time to collision (Regan & Vincent, 1995).

When the ratio $I/D(\mathrm{d}\delta/\mathrm{d}t)$ was the task-relevant variable, the values of $I/D(\mathrm{d}\delta/\mathrm{d}t)$ and the disparity displacement (i.e., $\Delta\delta$, the total change of disparity during a presentation) varied orthogonally within the set of 64 stimuli. In order to dissociate these two variables, the presentation duration (Δt) was varied by 40% about the mean of 650 msec so that the set of 64 stimuli consisted of different combinations of $I/D(\mathrm{d}\delta/\mathrm{d}t)$, $\Delta\delta$ and Δt. We chose to dissociate $\mathrm{d}\delta/\mathrm{d}t$ and $\Delta\delta$ because it has been claimed that discriminations of $\mathrm{d}\delta/\mathrm{d}t$ are based on $\Delta\delta$ rather than on $\mathrm{d}\delta/\mathrm{d}t$ (Harris & Watamaniuk, 1995)—though subsequent studies have shown this claim to lack general validity (Portfors-Yeomans & Regan, 1996; Portfors & Regan, 1997). The starting size did not vary within the set of 64 stimuli when the ratio $I/D(\mathrm{d}\delta/\mathrm{d}t)$ was the task-relevant variable. The mean value of $I/D(\mathrm{d}\delta/\mathrm{d}t)$ was 2.6 sec and the mean disparity displacement was 0.67 deg. Starting disparity was always 0.54 deg uncrossed. Target diameter was either 0.03 or 0.7 deg.

Discrimination thresholds were measured by the method of constant stimuli. Each trial consisted of a single presentation. The observer's task was to signal whether the time to collision was larger or smaller than the mean of the stimulus set.

Analysis of data. Psychometric functions were constructed by plotting the percentage of "larger than the mean time to collision" responses vs the particular variable that was task-relevant. Discrimination threshold for time to collision was estimated by submitting the psychometric function to Probit analysis (Finney, 1971). Discrimination threshold was defined as 0.5 ($T_{75} - T_{25}$), where T_{75} and T_{25} were, respectively, the time to collision for 75% and 25% "larger than the mean time to collision" judgements. We also subjected the responses to stepwise regression analysis. The following is from the handbook provided with the Statview II (Abacus Concepts Inc., Berkeley, CA, 1987) package that we used. "Statview computes a multiple linear regression using the forward stepwise regression with elimination of unnecessary variables. The forward selection procedure selects as the next variable for the regression model that independent variable with the highest partial correlation with the dependent variable. Essentially, the partial F-ratio associated with each remaining variable is computed based upon the inclusion of a remaining variable into the existing equation. Of those variables not included in the regression equation, that variable with the largest partial F-ratio is selected for inclusion and then new partial F-ratios are computed."

Results

In Fig. 2(A)–(D) the percentage of "later than the mean time to collision" responses were plotted vs the ratio $\theta/(\mathrm{d}\theta/\mathrm{d}t)$, the task-relevant variable. First, consider data for the large target (filled circles). The steepness of the

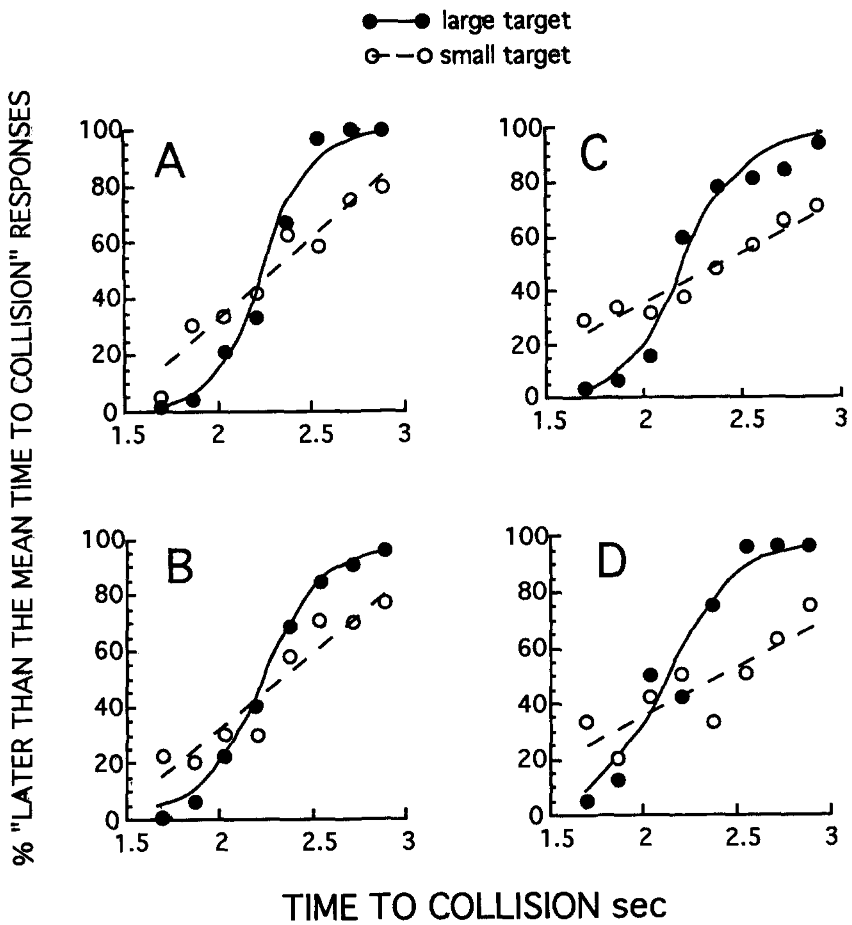

FIGURE 2. Discrimination of trial-to-trial variations of time to collision in the case that estimates were based on monocular information only. The percentage of "later than the mean time to collision" responses were plotted vs the time to collision. (A)–(D) are for observers 1–4, respectively.

psychometric functions in Fig. 2(A)–(D) indicates that responses were strongly influenced by trial-to-trial variations in the task-relevant variable. Discrimination thresholds for the ratio $\theta/(\mathrm{d}\theta/\mathrm{d}t)$ were estimated from the psychometric functions plotted as filled circles in Fig. 2(A)–(D). They were, respectively, 5.8 (SE = 0.7)%, 7.3 (SE = 0.9)%, 10 (SE = 1)% and 12 (SE = 2)% for observers 1, 2, 3 and 4, respectively. These findings were complemented by the results of stepwise regression analysis set out in Table 1. For the large target, the task-relevant variable accounted for a high proportion of the total variance (R^2 fell between 0.72 and 0.80). No other variable accounted for any significant additional variance, confirming previous reports that observers ignored the task-irrelevant variables θ, $\mathrm{d}\theta/\mathrm{d}t$ and $\Delta\theta$ when discriminating trial-to-trial variations in the ratio $\theta/(\mathrm{d}\theta/\mathrm{d}t)$ (Regan & Hamstra, 1993; Regan & Vincent, 1995). For completeness, we went on to calculate R^2 values for the task-irrelevant variables $\mathrm{d}\theta/\mathrm{d}t$ and $\Delta\theta$. The proportion of variance accounted for by either variable was negligibly small ($R^2 < 0.05$).

Next consider the data for the small target, plotted as open circles in Fig. 2(A)–(D). The comparatively shallow psychometric functions indicate that responses were less strongly influenced by trial-to-trial variations in the task-relevant variable $\theta/(\mathrm{d}\theta/\mathrm{d}t)$ than was the case for the large target (filled circles). Discrimination thresholds for the ratio $\theta/(\mathrm{d}\theta/\mathrm{d}t)$ were estimated from the psychometric functions plotted as open circles in Fig. 2(A)–(D). They were, respectively, 17 (SE = 3)%, 20 (SE = 3)%, 27 (SE = 4)% and 35 (SE = 4)% for observers 1, 2, 3 and 4, respectively. At first sight this finding might seem relevant to a previous report that estimated time to collision depends on target size (DeLucia, 1991). However, further analysis showed that the difference between the large-target and small-target data was much greater than indicated in Fig. 2(A)–(D). We subjected the response data to stepwise regression analysis, entering the variables $\theta/(\mathrm{d}\theta/\mathrm{d}t)$, $\mathrm{d}\theta/\mathrm{d}t$, θ and $\Delta\theta$. Table 1 shows that no variable or combination of variables accounted for more than a small part of the variance (R^2 fell between 0.15 and 0.42 for the task-relevant variable). And for two observers, a task-irrelevant variable accounted for the most variance.

Figure 3(A)–(D) shows binocular data for observers 1, 2, 4 and 5, respectively. The task-relevant variable was the ratio $I/D(\mathrm{d}\delta/\mathrm{d}t)$. Our main finding is that, in contrast to the expanding-size data shown in Fig. 2(A)–(D), the psychometric function for the large target (filled circles) was no steeper than the psychometric function for the small target (open circles). This held for all four observers. In Fig. 3(A), discrimination threshold was

TABLE 1. R^2 values obtained from stepwise multiple regression analysis of observers' time to collision discrimination responses in the case where discrimination was based on monocular information alone

	Stepwise regression				
Observer	Target size (deg)	Most significant variable	R^2	Next significant variable	R^2
1	0.7	$\theta/(d\theta/dt)$	0.79	NA	NA
	0.03	$\theta/(d\theta/dt)$	0.42	NA	NA
2	0.7	$\theta/(d\theta/dt)$	0.76	NA	NA
	0.03	θ	0.46	$d\theta/dt$	0.52
3	0.7	$\theta/(d\theta/dt)$	0.80	NA	NA
	0.03	$\theta/(d\theta/dt)$	0.15	NA	NA
4	0.7	$\theta/(d\theta/dt)$	0.72	NA	NA
	0.03	θ	0.42	$d\theta/dt$	0.46

Key: θ, object's angular subtense at the eye; $d\theta/dt$, rate of increase of angular subtense; NA, not applicable.

5.2 (SE = 0.8)% for the large target and 5.1 (SE = 0.6)% for the small target. Corresponding thresholds in Fig. 3(B) were 12.6 (SE = 0.9)% and 9.8 (SE = 0.9)%, in Fig. 3(C) 7.9 (SE = 0.7)% and 9.2 (SE = 0.9)%, and in Fig. 3(D) 7.0 (SE = 0.8)% and 8.2 (SE = 0.9)%. Statistical comparisons of discrimination thresholds for the large and small targets are described below (Experiment 5).

Next we subjected the response data shown in Fig. 3(A)–(D) to stepwise regression analysis. The variables entered were time to collision [i.e., the ratio $I/D(d\delta/dt)$], $\Delta\delta$ and the presentation duration (Δt). Table 2 shows that the task-relevant variable accounted for a high proportion of the total variance (R^2 ranged from 0.70 to 0.81), and that no other variable accounted for significant variance. This held for both the large and the small targets. These findings indicate that observers discriminated trial-to-trial variations in time to collision on the basis of trial-to-trial variations in $d\delta/dt$ and ignored trial-to-trial variations in disparity displacement. This conclusion is in line with evidence that both the detection (Cumming & Parker, 1994) and the discrimination (Portfors-Yeomans & Regan, 1996; Portfors & Regan, 1997) of stereomotion are based on the rate of change of disparity. In view of the claim that observers base judgements of the rate of

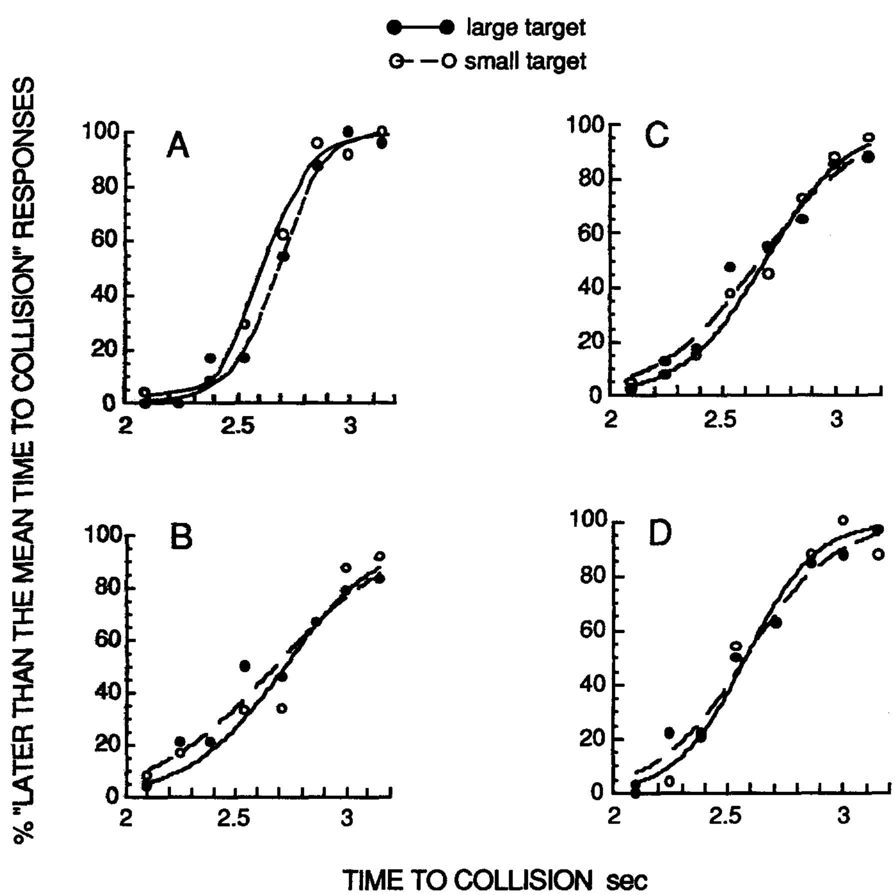

FIGURE 3. Discrimination of trial-to-trial variations of time to collision in the case that estimates were based on binocular information only. The percentage of "later than the mean time to collision" responses were plotted vs the time to collision. Filled circles are for the large target, and open circles are for the small target. (A)–(D) are for observers 1, 2, 4 and 5, respectively.

TABLE 2. R^2 values obtained from stepwise multiple regression analysis of observers' time to collision discrimination responses in the case where discrimination was based on binocular information only

Stepwise regression			
Observer	Target size (deg)	Most significant variable*	R^2
1	0.7	$I/D(d\delta/dt)$	0.80
	0.03	$I/D(d\delta/dt)$	0.80
2	0.7	$I/D(d\delta/dt)$	0.70
	0.03	$I/D(d\delta/dt)$	0.73
3	0.7	$I/D(d\delta/dt)$	0.81
	0.03	$I/D(d\delta/dt)$	0.75
5	0.7	$I/D(d\delta/dt)$	0.77
	0.03	$I/D(d\delta/dt)$	0.76

Key: I, interocular separation; D, object's distance; $d\delta/dt$, rate of increase of binocular disparity; NA, not applicable.
*No other variable considered was statistically significant.

change of disparity on trial-to-trial variations in disparity displacement (Harris & Watamaniuk, 1995) we went on to measure R^2 values for the change in disparity during a presentation (a task-irrelevant variable). The proportion of variance accounted for was negligible (R^2<0.2 in every case), confirming that our observers ignored trial-to-trial variations in disparity displacement.

Discussion

When estimates of time to collision are based entirely on the ratio $\theta/(d\theta/dt)$, target size has an even greater effect than is indicated in Fig. 2(A)–(D). It is not merely that the just-noticeable difference in the ratio $\theta/(d\theta/dt)$ is quantitatively higher for an 0.03 deg than for a 0.7 deg target. Rather, the distinction is qualitative. When the large target was used, observers based their responses on the task-relevant variable and ignored task-irrelevant variables. In contrast, when the small target was used, the task-relevant variable accounted for only a small proportion of the total variance, and for two observers a task-irrelevant variable accounted for more variance than the task-relevant variable. We conclude that our observers were essentially unable to perform the task of discriminating trial-to-trial variations in time to collision when the 0.03 deg target was used. This is not surprising, because finer and finer visual resolution is required to perform the task as target size is progressively reduced. In contrast, target size had no effect on discrimination performance when estimates of time to collision were based entirely on binocular information.

EXPERIMENT 2

Background and purpose

In Experiment 1 we found that monocular information does not provide a reliable basis for discriminating trial-to-trial differences in the time to collision with an approaching object when the object's size is small. It follows that monocular information would not provide a basis for accurately estimating the absolute time to collision with a small object. As stated earlier, a low discrimination threshold for time to collision is requisite for the ability to make accurate estimates of the time to collision with an approaching object on every single presentation.

However, it does not necessarily follow that, in everyday life, absolute estimates of the time to collision with a small approaching object are necessarily based on binocular information, because the absolute accuracy of time to collision estimates cannot be predicted from the discrimination threshold. It might be that an observer consistently over- or underestimates time to collision even though able to discriminate small differences in time to collision.

The purpose of Experiment 2 was to measure the degree to which observers either over- or underestimate absolute time to collision when the estimates are based entirely on the binocular cue $I/[D(d\delta/dt)]$. In the first part of Experiment 2 we used the 0.03 deg target. In the second part of Experiment 2 we used the 0.7 deg target, because we planned to go on to compare the accuracy of estimating time to collision when both binocular and monocular information was available with the accuracy of estimates based on only binocular or on only monocular information.

Methods

Apparatus. The apparatus was as described in General Methods.

Rationale. To ensure that starting disparity provided no cue to time to collision we arranged that all stimuli had the same starting disparity (0.54 min arc uncrossed, i.e., far disparity). To reduce the correlation between the total change of disparity during a presentation and the time to collision, we used three presentation durations. Varying the presentation duration also reduced the correlation between the final disparity of the target and the time to collision. This allowed us to assess the degree to which observers based their responses on the task-relevant variable $I/D(d\delta/dt)$ and ignored the task-irrelevant disparity displacement $\Delta\delta$.

Procedure. Bearing in mind that repeated exposure to a rate of change of disparity produces adaptation (Beverley & Regan, 1973) and our proposal that the perceived speed of motion-in-depth is inversely proportional to TTC rather than being determined by the approaching object's absolute speed (Regan & Hamstra, 1993), we designed our procedure so that each run contained a number of trials that was sufficiently few to avoid appreciable adaptation, but not so few that estimates of time to collision were unacceptably variable. Also, we used an inter-trial interval that was sufficiently long to minimize adaptation, yet not so long as to unduly prolong each run. A compromise was reached by trial and error in preliminary experiments.

Each trial consisted of one dichoptic presentation of the binocularly fused spots (Fig. 1). At time $t = 0$, the spots appeared and remained visible for a duration of Δt sec. At the designated time to collision, some time after the spots had been switched off, a brief auditory click was generated. The designated time to collision could be set to an accuracy of 0.001 sec. The observer was instructed to press one of two buttons depending on whether the click occurred before or after the simulated approaching sphere would have arrived at the eye.

The value of $(d\delta/dt)_{t=0}$ for the simulated approaching object was varied from trial to trial by the computer that controlled the experiment. Before any given trial, the computer set the starting time to collision [i.e., $I/D(d\delta/dt)_{t=0}$] on the basis of the observer's previous button presses. We used the staircase method described in detail and with its theoretical basis by Levitt (1971). For example, if the observer indicated that the simulated approaching sphere would have arrived before the auditory click, the time to collision was made longer for the next presentation in that particular staircase. Thus, the time to collision of the simulated object might be different on each successive trial.

Nine staircases were randomly interleaved. Three designated times to collisions were interleaved (1.67, 2.07 and 2.72 sec) with three different presentation durations (0.5, 0.7 and 0.9 sec), so that each staircase had a different combination of designated time to collision and presentation duration. On each of the nine staircases, the initial step size was 400 msec [a value determined by trial and error, see Levitt (1971)]. Step size was halved after the first reversal. The endpoint of each successive staircase was based on the final four reversals (the first two or more reversals were ignored). Each staircase converged onto a value of $I/D(d\delta/dt)_{t=0}$ that gave a 50% probability that the observer would judge that the simulated approaching object would arrive before the auditory click. We took this as the observer's estimate of the value of $I/D(d\delta/dt)_{t=0}$ that corresponded to a designated time to collision.

Data analysis. The difference between the designated and estimated time to collision for each of the nine staircases in any given run was obtained by calculating the percentage difference between the designated time to collision for that particular staircase and the value of the stimulus variable $I/D(d\delta/dt)_{t=0}$ corresponding to the 50% convergence point of that particular staircase. Each observer completed three runs, giving 27 estimates of time to collision. The mean percentage error of these 27 estimates was then calculated.

Observers were instructed to base their responses on the perceived time to collision of the simulated approaching object. In principle, however, observers might not base their responses entirely on the task-relevant variable [i.e., $I/D(d\delta/dt)$], and might place some weight on other variables. To check this point we subjected their responses to stepwise multiple regression analysis, entering the following variables: designated time to collision; presentation duration (Δt); disparity displacement ($\Delta\delta$); finishing disparity.

Results

The hatched and open bars in Fig. 4 show, respectively, the mean percentage difference between the designated and estimated times to collision for the large target and the small target for observers 1, 2 and 5, respectively. All three observers consistently overestimated time to collision. Percentage errors in estimating time to collision ranged from 2.5 to 9.8% for the large target and from 2.6 to 3.0% for the small target. For observer 1, the mean percentage error for the small target was not significantly different from the mean percentage error for the large target ($t = 0.4$, $P > 0.5$, $dF = 52$). For observers 2 and 5, the percentage errors were significantly lower for the small target ($t = 2.36$, $P < 0.05$, $dF = 52$ for observer 2; $t = 2.60$, $P < 0.05$, $dF = 52$ for observer 5).

Table 3 shows R^2 values obtained by stepwise multiple regression. The task-relevant variable [$I/D(d\delta/dt)$] accounted for a high proportion of total variance (R^2 ranged from 0.70 to 0.82). None of the other variables accounted for a statistically significant amount of variance. For completeness we used regression analysis to find the proportion of total variance accounted for by disparity displacement and by presentation duration. The R^2 values were very small, ranging from 0.14 to 0.29 for disparity displacement and from 0.01 to 0.02 for presentation duration.

Discussion

On the basis of binocular information alone, observers can make accurate estimates of time to collision with an approaching object, whether the object is small or large. The finding that the accuracy of judging time to collision can be higher for the small than for the large target might be due to the fact that the rate of change of disparity and the rate of change of size provided conflicting information: $d\delta/dt$ indicated that the target was approaching, while $d\theta/dt$ indicated that the target was stationary. (Indeed, for the larger target, observers reported an illusory contraction of size as it appeared to move closer.) Because the $d\theta/dt$ signal was much weaker for the small target than for the large target, this conflict would be much less for the small target.

Taken together, the results of Experiments 1 and 2 indicate that in everyday situations, when both monocular and binocular cues are available simultaneously, accurate estimates of time to collision will be based almost entirely on the binocular cue, when the approaching object is small and is no more than a few metres away.

EXPERIMENT 3

Purpose

The purpose of Experiment 3 was to measure the degree to which observers either overestimate or underestimate absolute time to collision when the estimates are based on the monocular cue $\theta/(d\theta/dt)$ alone.

Methods

Apparatus. The apparatus was as described in General Methods.

Procedure. We used a constant presentation duration (Δt). Consequently, had we used one starting size only,

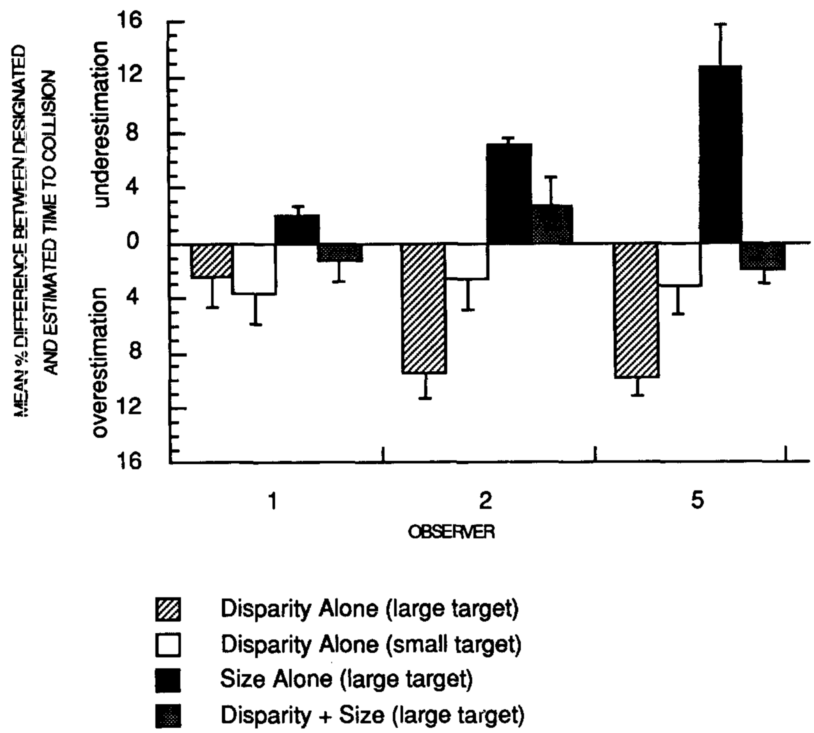

FIGURE 4. The mean percentage difference (and standard errors) between designated and estimated time to collision for observers 1, 2 and 5. Hatched bars: estimates based on binocular information alone (large target). Open bars: estimates based on binocular information alone (small target). Solid bars: estimates based on monocular information alone (large target). Grey bars: estimates based on combined binocular and monocular information (large target).

there would have been a correlation between the time to collision with the simulated approaching sphere [i.e. $\theta_{t=0}/(\mathrm{d}\theta/\mathrm{d}t)_{t=0}$] and the following variables: change of size during presentation $\Delta\theta$; initial rate of expansion $(\mathrm{d}\theta/\mathrm{d}t)_{t=0}$; final rate of expansion $(\mathrm{d}\theta/\mathrm{d}t)_{t=\Delta t}$. To reduce this correlation we interleaved three starting sizes (0.41, 0.68 and 0.9 deg) and three values of designated time to collision (1.69, 2.09, 2.72 sec). Each of the nine interleaved staircases had a different combination of time to collision and starting size. Presentation duration was 0.7 sec. To assess whether observers ignored all stimulus variables except the ratio $\theta/(\mathrm{d}\theta/\mathrm{d}t)$, we analyzed our response data by stepwise discriminate analysis entering the following variables: $\theta_{t=0}/(\mathrm{d}\theta/\mathrm{d}t)_{t=0}$; $(\mathrm{d}\theta/\mathrm{d}t)_{t=0}$; $(\mathrm{d}\theta/\mathrm{d}t)_{t=\Delta t}$; $\Delta\theta$.

Bearing in mind that repeated exposure to an expanding target produces adaptation (Regan & Beverley, 1978a,b, 1980; Beverley & Regan, 1979a,b) and our proposal that the perceived speed of motion-in-depth is inversely proportional to TTC rather than determined by the approaching object's absolute speed (Regan & Hamstra, 1993), we based our procedure on the same staircase method that we had designed to minimize the adaptation problem in Experiment 2.

Results

The solid bars in Fig. 4(A)–(C) show the mean percentage differences between the designated and estimated time to collision averaged over the three starting sizes for observers 1, 2 and 5, respectively. Confirming previous reports (Schiff & Detwiler, 1979; Cavallo & Laurent, 1988), all observers consistently underestimated time to collision. Percentage errors ranged from 2.0 to 12%.

Table 4 shows the results of subjecting the response data to stepwise multiple regression analysis. The task-relevant variable [i.e., the ratio $\theta/(\mathrm{d}\theta/\mathrm{d}t)$] accounted for a high proportion of the total variance (R^2 ranged from 0.80 to 0.91), and no other variable accounted for a significant amount of total variance.

In a subsidiary experiment, we found that errors in estimating time to collision were similar when the target was presented to one eye only as when identical targets were presented to both eyes.

Discussion

We conclude that, provided the target is sufficiently large, observers can make accurate judgements of time to collision based on the $\theta/(\mathrm{d}\theta/\mathrm{d}t)$ ratio alone, while ignoring simultaneous trial-to-trial variations in both target size, rate of expansion and total change in size.

EXPERIMENT 4

Purpose

The purpose of Experiment 4 was to measure the accuracy of time to collision estimates in the situation that both monocular and binocular retinal image information of comparable weighting were available. We chose the combination of monocular and binocular information appropriate for a real-world sphere simulated by the large target used in Experiments 1–3.

Methods

Apparatus. The apparatus was as described in General Methods.

Procedure and rationale. The procedure was the same as in Experiments 2 and 3, except that we interleaved three values of starting size, three values of time to collision and three values of presentation duration, giving a total of 27 conditions. Unfortunately, if we were to minimize problems with adaptation and length of runs, we could not interleave as many as 27 staircases during a single run. We chose to hold presentation duration constant during any given run and interleave nine staircases corresponding to the three starting sizes and three values of time to collision so that each of the nine staircases had a different combination of time to collision and starting size. The presentation duration was varied across runs with each observer performing three runs: one for each of the three values of presentation duration used in Experiment 2. The computer set the combination of $\theta t = 0/(\mathrm{d}\theta/\mathrm{d}t)_{t=0}$ and $I/\{D(\mathrm{d}\delta/\mathrm{d}t)_{t=0}\}$ that corresponded to one particular time to collision, and varied this time to collision on each successive trial on the basis of the observer's previous button presses.

Data analysis. Data were analyzed as in Experiments 2 and 3.

Results and discussion

The gray bars to the right of the black bars in Fig. 4 show percentage differences between estimated and designated time to collision. Errors ranged from 1.3 to 2.7%. We used a repeated-measures ANOVA to compare errors in estimating time to collision in the four experimental conditions used to collect all the data shown in Fig. 4. The overall F was significant at the $P = 0.05$ level [$F(3,6) = 6.6$]. Next we made pairwise comparisons of the four conditions using a *post-hoc* Tukey test. Results were as follows: (1) for the large target, errors in estimating time to collision were significantly lower when estimates were based on combined monocular and binocular information than when they were based on monocular information alone or binocular information alone; (2) in the case that estimates of time to collision were based on binocular information alone, errors were significantly lower for the small target than for the large target.

Discussion

We conclude that the absolute accuracy of estimating time to collision was significantly better when both binocular and monocular information were available than when only binocular or only monocular information was available.

Heuer (1993) compared the accuracy of estimating time to collision based on a combination of binocular and monocular information with the accuracy using only binocular information or only monocular information. He also concluded that accuracy was improved when both binocular and monocular information were available. However, it is difficult to assess this conclusion, because errors in estimating time to collision were very much larger than those we report. For example, Fig. 2 in Heuer (1993) shows that when only binocular information was available an actual time to collision of 2.0 sec was estimated to be 3.8 sec. This 90% error is far greater than the 2.6–3% errors that we report here. Again, when only monocular information was available, an actual time to collision of 2.0 sec was estimated to be 3.0 sec, a 50% error that is far greater than the 2–12% errors we report here. In addition, Heuer reported that estimates based on monocular information were overestimates rather than the underestimates reported here and by previous authors. One possible reason for the disagreement as to data is that we provided observers with a time reference (a click) that was accurate to 0.001 sec, while Heuer's observers were instructed to press a key when they judged that the simulated object would have arrived. It may also be relevant that his experimental design made no provision for checking that observers ignored all task-irrelevant variables, and based their estimates entirely on whichever variable was task-relevant.

The finding that monocular and binocular information in environmentally-correct proportions combine to improve the psychophysical accuracy of time to collision estimates has a physiological parallel. Erkelens and Regan (1986) showed that the phase lag of ocular vergence oscillations produced by simulating the eyes with disparity oscillations is reduced when environmentally-correct size oscillations are added to the binocular stimulus.

TABLE 3. R^2 values obtained from stepwise multiple regression analysis of observers' estimates of the absolute time to collision with a simulated approaching object in the case where estimates were based on binocular information only

	Stepwise regression		
Observer	Target size (deg)	Most significant variable*	R^2
1	0.7	$I/D(\mathrm{d}\delta/\mathrm{d}t)$	0.75
	0.03	$I/D(\mathrm{d}\delta/\mathrm{d}t)$	0.76
2	0.7	$I/D(\mathrm{d}\delta/\mathrm{d}t)$	0.76
	0.03	$I/D(\mathrm{d}\delta/\mathrm{d}t)$	0.78
5	0.7	$I/D(\mathrm{d}\delta/\mathrm{d}t)$	0.82
	0.03	$I/D(\mathrm{d}\delta/\mathrm{d}t)$	0.70

*No other variable considered was statistically significant.

TABLE 4. R^2 values obtained from stepwise multiple regression analysis of observers' estimates of the absolute time to collision with a simulated approaching object in the case where estimates were based on monocular information only

	Stepwise regression		
Observer	Target size (deg)	Most significant variable*	R^2
1	0.7	$\theta/(\mathrm{d}\theta/\mathrm{d}t)$	0.86
2	0.7	$\theta/(\mathrm{d}\theta/\mathrm{d}t)$	0.91
5	0.7	$\theta/(\mathrm{d}\theta/\mathrm{d}t)$	0.80

*No other variable considered was statistically significant.

GENERAL DISCUSSION

A binocular cue to time to collision

We conclude that observers can make accurate estimates of absolute time to collision entirely on the basis of rate of change of binocular disparity—at least for the close viewing distance of 1.6 m that we used—and that neither the accuracy of estimating time to collision nor the just-noticeable difference in time to collision is degraded by reducing the target size from 0.7 to 0.03 deg.

We found that monocular information does not provide a reliable basis for discriminating trial-to-trial variations in the time to collision with a small approaching object. We conclude that, in everyday conditions, accurate estimates of time to collision will be based almost entirely on binocular information when the object is small, provided that the combination of the object's distance and approach speed place the rate of change of disparity sufficiently above detection threshold.

Many previous studies on visual judgements of time to collision either eliminated binocular disparity information altogether (Todd, 1981; Schiff & Detwiler, 1979; McLeod & Ross, 1983; DeLucia, 1991; Sekuler, 1992; Regan & Hamstra, 1993; Regan & Vincent, 1995) or, when disparity information has been available, it was confounded with monocular information (Lee *et al.*, 1982; Lee *et al.*, 1983; Warren *et al.*, 1986; Savelsbergh *et al.*, 1991; Bootsma & van Wieringen, 1990). Suggestive evidence that binocular retinal image information might aid judgement of time to collision has been scattered through the literature over a long period. For example, one hint was provided by Banister and Blackburn (1931) who ranked 258 Cambridge undergraduates into "poor" and "good" categories according to their ability at ball games, and found that the group who were ranked "good" had a larger interpupillary distance than the group ranked as "poor". More recently, using high-speed photography it was found that, when catching a ball with one hand, the temporal organization of finger flexions was disrupted when the lights were switched off 275 msec before the ball arrived, that is when the ball was closer than 6 ft from the hand, when binocular processing would be maximally effective (Alderson, Sully, & Sully, 1974). These finger flexions are necessary if the ball is to be retained in the catcher's grip. Binocular vision seems to be important also at distances relevant to highway driving. Cavallo and Laurent (1988) compared the accuracy of time to collision judgements using binocular vs monocular vision on a circuit under actual driving conditions. Accuracy was greater for binocular judgements, provided that viewing distance was less than approx. 75 m, but errors were still considerable (time to collision was consistently underestimated by at least 30%). However, at the considerably greater distances associated with landing a jet aircraft, occluding one eye during the landing approach had no detrimental effect on landing performance (Pfaffmann, 1948; Lewis & Kriers, 1969; Lewis, Blakely, Swaroop, Masters, & McMurty, 1973; Grosslight, Fletcher, Masterton, & Hagen, 1978).

A monocular correlate of time to collision

Although discussion of results focused entirely on the monocular $\theta/(d\theta/dt)$ cue to time to collision, valid binocular information was available to the participants in some field studies (Bootsma, 1991; Lee *et al.*, 1982, 1983), and it is difficult to be sure that the participants ignored this binocular information. Much, though not all (DeLucia, 1991), of the previous laboratory research on time to collision using monocular information only was on judging which of two approaching objects would arrive first (Todd, 1981), or on discriminating variations in time to collision (Sekuler, 1992; Regan & Hamstra, 1993; Regan & Vincent, 1995). From the results of Experiment 3 we conclude that observers can make accurate estimates of absolute time to collision on the basis of monocular information alone and that, for objects whose starting sizes are in the range 0.4–1.0 deg, absolute errors range from 2 to 12% over a 1.7–2.7 sec range of times to collision.

Combined binocular and monocular information about time to collision

For the large target, estimates of time to collision were more accurate when both binocular and monocular retinal image information was available (as is the case in everyday life) than when only binocular or only monocular information was available. Absolute errors could be as small as 1.3%. If we assume that a cricket or table tennis player can use visual information about the time of arrival of the ball up to about 300 msec before the instant of impact with a bat, a 1.3% error approaches the performance required to account for the 2.0–2.5 msec accuracy with which top sports players can judge the time to impact with an approaching ball (Regan, Beverley & Cynader, 1979; Bootsma & van Wieringen, 1990).

One possible reason for the larger errors in estimating time to contact in the situation that disparity changes while size remains constant or that size changes while disparity remains constant is that the two cues are providing conflicting information about the simulated object's motion-in-depth. This simple idea is consistent with the finding (Experiment 2) that estimates based on binocular information could be more accurate when conflicting monocular information was effectively removed by using a small target. On the other hand, estimates based on monocular information alone were similar when the target was presented to one eye or when identical targets were presented to both eyes. Given that presentation to eye only removes binocular information (i.e., that disparity is constant) that conflicts with the monocular information conveyed by the target's rate of expansion, the finding might seem to reject the "conflict" hypothesis. However, our failure to find improved accuracy might be because improvement only occurs when conflict is removed in situations that observers commonly experience in everyday life. Throughout their visual development, normally-sighted two-eyed individuals would seldom attempt to catch, hit or avoid an approaching object while viewing it with one eye. On the other hand it is the everyday situation that, when the approaching object is small, stimulation by $d\theta/dt$ is weak or even subthreshold. Whether errors in estimating time to collision with a large approaching object on the basis of monocular information alone would be less for an observer who lost the use of an eye in early life remains to be shown.

REFERENCES

Alderson, G. J. K., Sully, D. J. & Sully, H. G. (1974). An operational analysis of a one-handed catching task using high-speed photography. *Journal of Motor Behaviour, 6*, 217–226.

Banister, H. & Blackburn, J. M. (1931). An eye factor affecting proficiency at ball games. *British Journal of Psychology, 21*, 382–384.

Beverley, K. I. & Regan, D. (1973). Evidence for the existence of neural mechanisms selectively sensitive to the direction of movement in space. *Journal of Physiology, 235*, 17–29.

Beverely, K. I. & Regan, D. (1979a). Separable aftereffects of changing-size and motion-in-depth: different neural mechanisms? *Vision Research, 19*, 727–732.

Beverley, K. I. & Regan, D. (1979b) Visual perception of changing-size: the effect of object size. *Vision Research, 19*, 1093–1104.

Bootsma, R. J. (1991). Predictive information and the control of action. *International Journal of Sports Psychology, 22*, 271–278.

Bootsma, R. J. & van Wieringen, P. C. W. (1990). Timing an attacking forehand drive in table tennis. *Journal of Experimental Psychology: Human Perception and Performance, 16*, 21–29.

Cavallo, V. & Laurent, M. (1988). Visual information and skill level in time-to-collision estimation. *Perception, 17*, 623–632.

Collewijn, H. & Erkelens, C. J. (1990). Binocular eye movements and the perception of depth. In Kowler, E. (Ed.), *Eye movements and their role in visual and cognitive processes* (pp. 213–261). Amsterdam: Elsevier.

Cumming, B. G. & Parker, A. J. (1994). Binocular mechanisms for detecting motion in depth. *Vision Research, 34*, 483–495.

DeLucia, P. R. (1991). Pictorial and motion-based information for depth perception. *Journal of Experimental Psychology: Human Perception and Performance, 17*, 738–748.

Erkelens, C. J. & Collewijn, H. (1985a) Motion perception during dichoptic viewing of moving random-dot stereograms. *Vision Research, 25*, 583–588.

Erkelens, C. J. & Collewijn, H. (1985b) Eye movements and stereopsis during dichoptic viewing of moving random-dot stereograms. *Vision Research, 25*, 1689–1700.

Finney, D. J. (1971). *Probit analysis*. Cambridge: Cambridge University Press.

Grosslight, J. H., Fletcher, H. J., Masterton, R. B. & Hagen, R. (1978). Monocular vision and landing performance in general aviation pilots: cyclops revisited. *Human Factors, 20*, 127–133.

Harris, J. M. & Watamaniuk, S. N. J. (1995). Speed discrimination of motion in depth using binocular cues. *Vision Research, 35*, 885–896.

Heuer, H. (1993). Estimates of time to contact based on changing size and changing target vergence. *Perception, 22*, 549–563.

Hong, X. H. & Regan, D. (1989). Visual field defects for unidirectional and oscillatory motion in depth. *Vision Research, 29*, 809–819.

Hoyle, F. (1957). *The black cloud* (pp. 26–27). London: Penguin Books.

Karnavas, W. J., Bahill, A. T. & Regan, D. (1990). Sensitivity analysis of a model for the rising fastball and breaking curveball. Proceedings of the IEEE Conference on Systems, Man and Cybernetics, Los Angeles.

Kruk, R. & Regan, D. (1983). Visual test results compared with flying performance in telemetry-tracked aircraft. *Aviation, Space and Environmental Medicine, 54*, 906–911.

Lee, D. N. (1976). A theory of visual control of braking based on information about time-to-collision. *Perception, 5*, 437–459.

Lee, D. N. & Lishman, J. R. (1977). Visual control of locomotion. *Scandinavian Journal of Psychology, 18*, 224–230.

Lee, D. N., Lishman, J. R. & Thomson, J. A. (1982). Visual regulation of gait in long jumping. *Journal of Experimental Psychology: Human Perception and Performance, 8*, 448–459.

Lee, D. N., Young, D. S., Reddish, D. E., Lough, S. & Clayton, T. M. H. (1983). Visual timing in hitting an accelerating ball. *Quarterly Journal of Experimental Psychology, 35A*, 333–346.

Levitt, H. (1971). Transformed up–down methods in psychoacoustics. *Journal of the Acoustical Society of America, 49*, 65–69.

Lewis, C. E.Jr., Blakeley, W. R., Swaroop, R., Masters, R. L. & McMurty, T. C. (1973). Landing performance by low-time private pilots after the sudden loss of binocular vision—Cyclops II. *Aerospace Medicine, 44*, 1241–1245.

Lewis, C. E.Jr. & Kriers, G. E. (1969). Flight research program: XIV. Landing performance in jet aircraft after the loss of binocular vision. *Aerospace Medicine, 44*, 957–963.

McLeod, R. W. & Ross, H. E. (1983). Optic-flow and cognitive factors in time-to-collision estimates. *Perception, 12*, 417–423.

Pfaffmann, C. (1948). Aircraft landings without binocular cues: a study based upon observations made in flight. *American Journal of Psychology, 61*, 323–335.

Portfors-Yeomans, C. V. & Regan, D. (1996). Cyclopean discrimination thresholds for the direction and speed of motion in depth. *Vision Research, 36*, 3279–3625.

Portfors, C. V. & Regan, D. (1997). Just-noticeable difference in the speed of cyclopean motion in depth and of cyclopean motion within a frontoparallel plane. *Journal of Experimental Psychology: Human Perception and Performance, 23*, 1074–1086.

Regan, D. (1991a) Specific tests and specific blindness: keys, locks and parallel processing. *Optometry and Vision Science, 68*, 489–512.

Regan, D. (1991b). Depth from motion and motion in depth. In Regan, D. (Ed.), *Binocular vision* (pp. 137–169). London: Macmillan.

Regan, D. (1995). Spatial orientation in aviation: visual contributions. *Journal of Vestibular Research, 5*, 455–471.

Regan, D. & Beverley, K. I. (1978a) Looming detectors in the human visual pathway. *Vision Research, 18*, 415–421.

Regan, D. & Beverley, K. I. (1978b) Illusory motion in depth: aftereffect of adaptation to changing size. *Vision Research, 18*, 209–212.

Regan, D. & Beverley, K. I. (1979). Binocular and monocular stimuli for motion in depth: changing-disparity and changing-size feed the same motion-in-depth stage. *Vision Research, 19*, 1331–1342.

Regan, D. & Beverley, K. I. (1980). Visual responses to changing size and to sideways motion for different directions of motion in depth: linearization of visual responses. *Journal of the Optical Society of America, 11*, 1289–1296.

Regan, D., Beverley, K. I. & Cynader, M. (1979). The visual perception of motion in depth. *Scientific American, 241*, 136–151.

Regan, D., Erkelens, C. J. & Collewijn, H. (1986a) Necessary conditions for the perception of motion in depth. *Investigative Ophthalmology and Visual Science, 27*, 584–597.

Regan, D., Erkelens, C. J. & Collewijn, H. (1986b) Visual field defects for vergence eye movements and for stereomotion perception. *Investigative Ophthalmology and Visual Science, 27*, 806–819.

Regan, D. & Hamstra, S. (1993). Dissociation of discrimination thresholds for time to contact and for rate of angular expansion. *Vision Research, 33*, 447–462.

Regan, D. & Vincent, A. (1995). Visual processing of looming and time to contact throughout the visual field. *Vision Research, 35*, 1845–1857.

Richards, W. & Regan, D. (1973). A stereo field map with implications for disparity processing. *Investigative Ophthalmology and Visual Science, 12*, 904–909.

Savelsbergh, G. J. P., Whiting, H. T. A. & Bootsma, R. J. (1991). Grasping Tau. *Journal of Experimental Psychology: Human Perception and Performance, 17*, 315–322.

Schiff, W. & Detwiler, M. L. (1979). Information judged in impending collision. *Perception, 8*, 647–658.

Sekuler, A. (1992). Simple-pooling of unidirectional motion predicts speed discrimination for looming stimuli. *Vision Research, 32*, 2277–2288.

Todd, J. T. (1981). Visual information about moving objects. *Journal of Experimental Psychology, 7*, 795–810.

Tresilian, J. R. (1995). Perceptual and cognitive processes in time-to-contact estimation: analysis of prediction-motion and relative judgment tasks. *Perception and Psychophysics, 57*, 231–245.

Tyler, C. W. (1975). Characteristics of stereomovement suppression. *Perception and Psychophysics, 17*, 225–230.

Tyler, C. W. (1991). Cyclopean vision. In Regan, D. (Ed.), *Binocular vision* (pp. 38–74). London and Baton Rouge: CRC Press.

Warren, W. H., Young, D. S. & Lee, D. N. (1986). Visual control of step length during running over irregular terrain. *Journal of Experimental Psychology: Human Perception and Performance, 12*, 259–266.

Wheatstone, C. (1852). Contributions to the physiology of vision II. *Philosophical Transactions of the Royal Society, Lond., 142*, 1–18.

Acknowledgements—We thank Matthew Sue-Ping, Jason Lawrence, Dahlia Dawlish, and Laurinda Kwan for their patience as observers in this experiment. This research was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC operating grant to D. R.). Effort sponsored by the Air Force Office of Scientific Research, Air Force Material Command, USAF, under grant number F49620-97-1-0051. The U.S. Government is authorized to reproduce and distribute reprints for governmental purposes notwithstanding any copyright violation thereon. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the Air Force Office of Scientific Research or of the U.S. Government. D. R. holds the NSERC/CAE Industrial Research Chair in Vision in Aviation. R. G. was supported by an NSERC Graduate Scholarship.

APPENDIX

In Fig. 5(A) and (B), an object of width $2s$ is moving at instantaneous speed V_z along a straight line that passes through point C midway between the eyes. At times $t = 0$ and $t = \Delta t$, the object's distances from point C are, respectively D and $(D - \Delta D)$, where $\Delta D \ll D$. For convenience, the resulting change in angular subtense $(\Delta\theta = \theta_2 - \theta_1)$ is illustrated in Fig. 5(A), and the resulting change in relative disparity $(\Delta\delta)$ is illustrated in Fig. 5(B).

It has been found that a rate of change of absolute disparity produces either no sensation of motion-in-depth (for a spatially extended dotted target) or (for a single-dot target) a much weakened sensation of motion-in-depth compared with that produced by a rate of change of relative disparity (Erkelens & Collewijn, 1985a,b; Regan *et al.*, 1986). That is the reason why we calculate disparities relative to a visible reference mark at an arbitrary location M in Fig. 5(B). Also in Fig. 5(B), P is a point on the object at time $t = 0$. The disparity of P relative to M is $\delta_{t=0}$, where:

$$\delta_{t=0} = \alpha_L + \alpha_R. \tag{A1}$$

At time $t = \Delta t$, the location of P has moved to P′, whose disparity relative to M is $\delta_{t=\Delta t}$, where

$$\delta_{t=\Delta t} = \alpha'_L + \alpha'_R. \tag{A2}$$

The change $(\Delta\delta)$ in disparity is given by

$$\Delta\delta = \alpha_{t+\Delta t} - \alpha_{t=0}. \tag{A3}$$

Hence, as shown previously (Regan & Beverley, 1979), if $\Delta t \rightarrow 0$, we have

$$\frac{d\theta}{dt} \approx \frac{2s}{D^2}\left(\frac{dD}{dt}\right) \tag{A4}$$

and

$$\frac{d\delta}{dt} \approx \frac{I}{D^2}\left(\frac{dD}{dt}\right). \tag{A5}$$

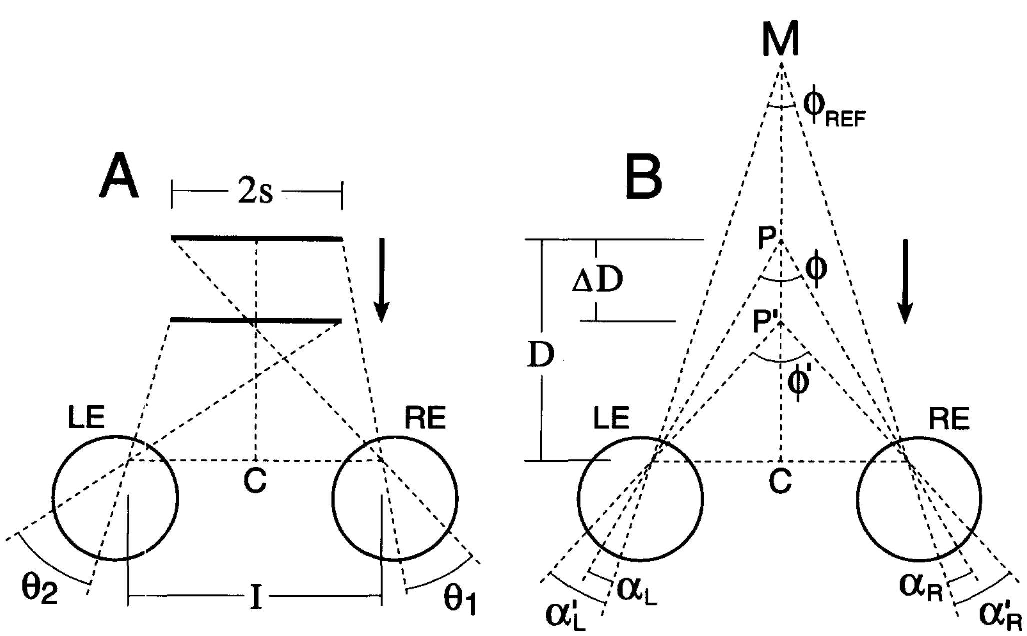

FIGURE 5. (A) An object of width $2s$ moves at an instantaneous velocity V_z on a straight line through a point C midway between the eyes. The angular subtense of the object (θ) increases from θ_1 at time $t = 0$ to θ_2 at time $t = \Delta t$. (B) A point object, located at P at a distance D from the eyes, moves at an instantaneous velocity V_z on a straight line through a point C midway between the eyes. At time $t = \Delta t$, the object is located at P′ and has travelled a distance ΔD. The disparity of the object (δ) relative to a stationary reference mark (M) changes from $\alpha_R + \alpha_L$ at time $t = 0$ to $\alpha'_R + \alpha'_L$ at time $t = \Delta t$. The change in disparity $(\Delta\delta)$ is equivalent to $\phi' - \phi$. LE: left eye. RE: right eye. I: interpupillary distance.

By combining A(4) and A(5) we have

$$\frac{(\mathrm{d}\theta/\mathrm{d}t)}{(\mathrm{d}\delta/\mathrm{d}t)} \approx \frac{2s}{I}, \tag{A6}$$

where $2s$ is the object's width, I is the observer's interpupillary separation and $D \gg I$ and $D \gg s$ (Regan & Beverley, 1979).

A(6) can be stated as follows. The ratio between the magnitudes of the monocular (i.e. $\mathrm{d}\theta/\mathrm{d}t$) and binocular (i.e. $\mathrm{d}\delta/\mathrm{d}t$) correlates of a sphere's motion-in-depth is proportional to the object's absolute width ($2s$) and inversely proportional to the observer's interpupilliary separation but does not depend on the object's distance.

A further point. Because the object's speed V_z equals $\mathrm{d}D/\mathrm{d}t$, A(4) can be rewritten as

$$V_z \approx \frac{D^2}{2s}\left(\frac{\mathrm{d}\theta}{\mathrm{d}t}\right) \tag{A7}$$

and A(5) can be rewritten as:

$$V_z \approx \frac{D^2}{I}\left(\frac{\mathrm{d}\delta}{\mathrm{d}t}\right). \tag{A8}$$

If V_z is constant, then from A(8)

$$T \approx \frac{I}{D(\mathrm{d}\delta/\mathrm{d}t)}, \tag{A9}$$

where the object will reach point C at time $t = T$ (Regan, 1995).

A(9) relates the object's time to collision (T) at time $t = 0$ with its instantaneous rate of change of disparity and distance at time $t = 0$. Note that, in contrast with equation (1), object distance enters into A(9).

Now we consider how the approaching object's relative disparity varies through the course of its trajectory. From A(3) and Fig. 5(B) we have

$$\Delta\delta \approx \frac{I\Delta D}{D^2}. \tag{A10}$$

This allows us to calculate the change in relative disparity ($\delta_{t=t} - \delta_{t=0}$) between time $t = 0$ and arbitrary time t. If we let $\Delta t \rightarrow 0$, then

$$\delta_{t=t} - \delta_{t=0} \approx I \int_{D=D_0}^{D=Dt} \frac{dD}{D^2} = \frac{It}{D_0 T(1 - t/T)} \tag{A11}$$

where D_0 is the object's distance at time $t = 0$, D_t is the object's distance at time $t = t$ and T is the time to collision at time $t = 0$.

Suppose we create the same temporal variation of relative disparity for different values of initial relative disparity (i.e., for different values of D_0). This will result in different values of T. For example, if D_0' is the new distance at time $t = 0$, then from Eq. (A7)

$$\frac{T'}{T} = \frac{D_0}{D_0'}, \tag{A12}$$

where T' is the new time to collision at time $t = 0$. Because we have restricted our discussion to relative disparity (i.e., disparity of P with respect to point M), equations A(11) and A(12) hold independently of whether the observer maintains constant vergence or tracks the approaching object. However, in principle, it does not necessarily follow from this geometrical fact that the observer's vergence would have no effect on psychophysical data, because a rate of change of vergence might affect the way in which a rate of change of disparity is processed. Perhaps this possibility can be discounted on the empirical grounds that a large rate of change of vergence does not create a perception of motion-in-depth, nor does it affect the detection threshold for rate of change of disparity (Regan *et al.*, 1986a).